Laboratory Astrophysics using an XRS Engineering Model Microcalorimeter

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Abstract. We have recently deployed an XRS (the X-ray Spectrometer on the *Astro-E* mission) engineering model microcalorimeter at the electron beam ion traps (EBIT I/II) at Lawrence Livermore National Laboratory. The EBIT I/II can produce well defined astrophysically interesting plasmas for a wide range of plasma conditions. The XRS engineering model was mated with a 32 element XRS 6x6 microcalorimeter array and integrated into a laboratory cryostat. The system was then transported to the EBIT I/II and operated over the last year. The microcalorimeter array has a composite resolution of 8 eV at 1 keV and 11 eV at 6 keV. During the campaign, we performed a number of high resolution, broad band observations including: K and L shell Fe with single ionization energies from 1 - 8 keV, Maxwellian distributions of Fe with $\langle kT \rangle = 0.5$ - 3 keV, non-equilibrium states of Fe with very fine time resolution for $\eta = 10^9$ - 10^{12} s cm^{-3}. The total observation time for the campaign was over 10 Ms and the analysis is ongoing. We will present here an overview of the instrument and a few of the preliminary results. The results of these experiments show the power and promise of the XRS microcalorimeter and give a detailed picture of how the instrument would have performed in orbit on Astro-E, and will perform in the future on the Astro-E2 mission.

With the launch of the *Chandra* and *XMM* x-ray observatories, a large quantity of high-resolution x-ray spectra have become available. This allows detailed plasma diagnostics to be performed for a wide range of celestial objects. However, this puts additional emphasis on the accuracy and precision of the atomic models used to interpret this data. For the past decade, our laboratory astrophysics program has provided detailed experimental input for the atomic codes using the electron beam ion traps EBIT I/II at the Lawrence Livermore National Laboratory (LLNL). This is a long-standing collaboration between LLNL, Columbia University, and recently NASA/GSFC. The results have strengthened both the atomic codes themselves and also our confidence that the atomic codes provide correct interpretation of astrophysical data. Here we report the continuation of this work using an XRS microcalorimeter detector array in conjunction with high-resolution crystal spectrometers.

EBIT I and II produce collisionally excited plasmas of astrophysically interesting species (including C, O, N, Ar, Si, S, Fe) with well-controlled physical parameters. The electron energy can be either monoenergetic or a quasi-Maxwellian distribution. The Maxwellian electron distribution allows the study of thermal plasmas with electron temperatures from 0.5-4 keV. EBIT I/II operate at a nominal electron density of

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$\sim 10^{12}$ cm^{-3}, similar to many astrophysical sources. In addition, the repeated injection of ions into the trap allows the detailed study of x-ray emission from plasmas between strongly non-equilibrium and fully equilibrium ionization conditions.

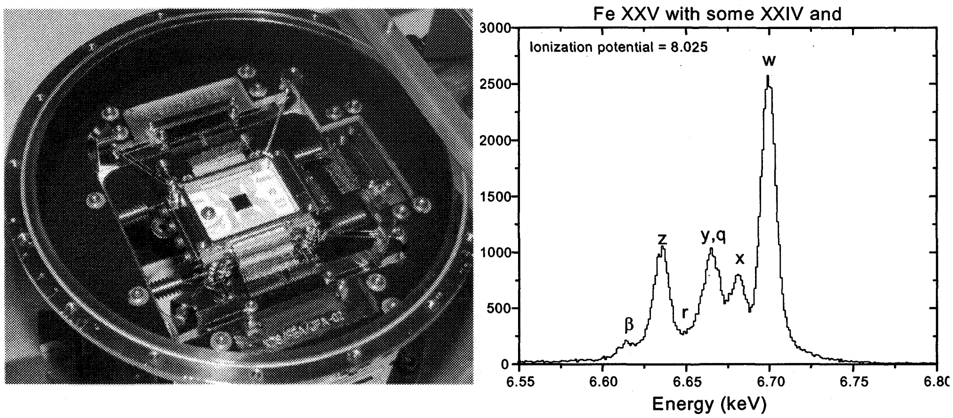

FIGURE 1. (a) The XRS engineering model detector assembly with a 6x6 microcalorimeter array in the center. (b) a spectrum of He-like Fe K-shell emission taken with the XRS at the EBIT I/II facility.

We have recently deployed an XRS engineering model detector system at the EBIT I/II facility [1] as shown in Fig. 1(a). The XRS microcalorimeter system adds a unique broadband (0.3-10 keV), highly efficient (> 95% Q.E.), and moderate resolution (~11 eV FWHM at 6 keV) capability to the laboratory astrophysics program at LLNL. The detector system is composed of a 32-pixel microcalorimeter array with a total collecting area of 13 mm^2. The system is installed in a small laboratory cryostat with a 60 g adiabatic demagnetization refrigerator which cools the detector to its 60 mK operating temperature. The rest of the system, including the cold front-end electronics and the room temperature amplifiers and pulse processing electronics, are engineering model systems from the XRS program. The XRS/EBIT spectrometer, being essentially a copy of the XRS spectrometer from Astro-E, benefits from the extensive experience and calibration data from the XRS program. In addition, we have integrated a GPS timing system with the XRS/EBIT giving absolute event time tags with 10 μs precision. This is especially important for use with EBIT I/II where the ionization conditions vary with time after injection.

During our first experimental run at the EBIT I/II facility we acquired in excess of 10 Ms of observation data. This included detailed studies of Fe L and K shell emission with monoenergetic electron energies from 0.5-8.0 keV and thermal distributions from 0.5-3.0 keV [2]. As an example, Fig. 1(b) shows a 20 ks spectrum of K shell emission from He-like Fe XXV with some Fe XXIV and XXIII using a monoenergetic electron beam acquired using the XRS/EBIT.

Timing is critically important to operating at the EBIT I/II facility. The EBIT cycle consists of ion injection either from a metal vapor vacuum arc (MEVVA) or from a gas injector. The ions are then trapped and further ionized by an electron beam and a pair of Helmholtz coils. During trapping, we can study collisional excitation and photoexcitation and, with the electron beam off, charge exchange with neutral atoms. The trap is then dumped and the injection process is repeated. The entire cycle runs from as little as 1 ms to 5 or more seconds per injection. The flux is relatively modest (up to 100 cps/pixel on the XRS) so that many injection cycles are needed to form a spectrum. During the initial phase right after injection, the ions are not in ionization equilibrium with the electron energy. This is equivalent to what occurs behind a shock front in a young supernova remnant. Fig. 2(a) shows a pulse height vs. time plot of the x-ray emission lines right after injection taken with the XRS using phase folded spectra from 10^4 EBIT injection cycles. The horizontal stripes are the characteristic L shell emission lines for Ne-like Fe XVII through Li-like Fe XXIV. Fig. 2(b) shows the relative flux vs. time for several of the bright emission lines. Note that the plasma does not reach ionization equilibrium until more than 300 ms after injection. Without precision timing, the equilibrium spectra would have a large contribution from bright low-ionization state emission lines, substantially confusing the interpretation of the results.

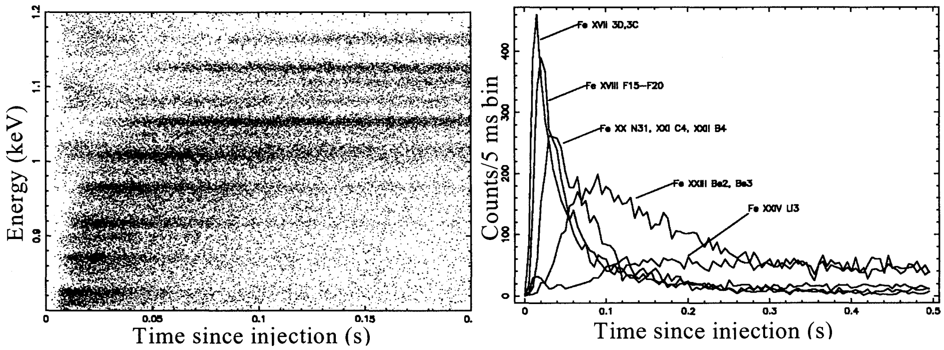

FIGURE 2. (a) x-ray energy vs. time for each event and (b) x-ray flux in bright Fe L shell lines as a function of time after Fe injection into the EBIT I/II. Note that in steady state (t>0.4 s) the spectrum is dominated by Fe XXIII and XXIV but at earlier times all ionization species from Fe XVII-XXIV are represented.

The intrinsic XRS timing precision was established to time-tag events on the Astro-E satellite. The events are time tagged to 10 μs precision using the flight digital pulse processing electronics [3]. For operation at EBIT we combined the pulse timing and EBIT I/II timing with a GPS time-tagging instrument. This allows relative timing between the XRS and EBIT I/II with the full 10 μs XRS precision. It is then a simple matter to fold the observation on the EBIT injection phase. Single observations can span up to the 15 hour ADR hold time without interruption.

Another major benefit of precision timing is that we can not only study clean-equilibrium phenomena with the EBIT I/II but non-equilibrium phenomena as well. This opens up the possibility of providing key-diagnostics for the interpretation of non-equilibrium plasmas, especially in young supernova remnants. Decaux et al. [4] have discovered key-diagnostic signatures in K-shell Fe for non-equilibrium plasmas at the EBIT II. With the combination of the XRS and a suite of very high resolution crystal spectrometers, we are able to investigate similar diagnostics using lower temperature Fe L shell emission. Fig. 3(a) shows the emission from a 5 ms time slice 10 ms after

Fe injection using 10^4 EBIT injection cycles acquired with the XRS. This gives an ionization parameter of $\eta=5\times10^9$ s cm^{-3}. The dominant species early in the injection cycle are Ne-like Fe XVII and F-like Fe XVIII. Fig. 3(b) shows the equilibrium state of the same plasma integrated from 0.5 s ($\eta>3\times10^{11}$ s cm^{-3}) to the end of the 5 s injection cycle. Here the dominant species are Be-like Fe XXIII and Li-like Fe XXIV. At intermediate times, all species are represented from Fe XVII-XXIV in ratios far from the equilibrium ionization values.

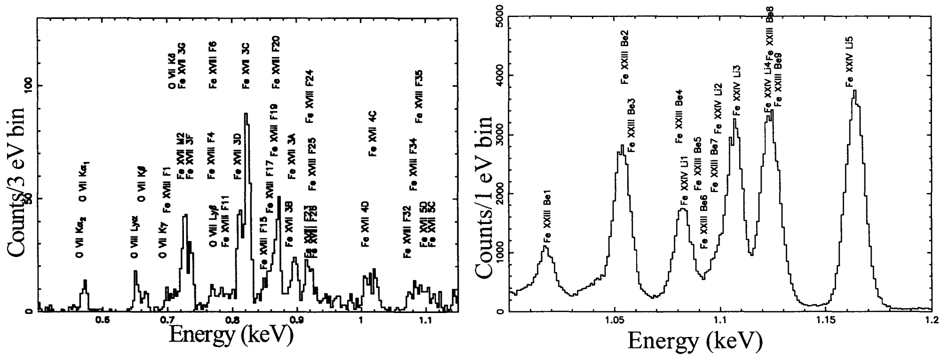

FIGURE 3. (a) Fe L-shell emission is dominated by Fe XVII and XVIII 10 ms after injection. (b) At t>0.5 s the plasma is in equilibrium and is dominated by Fe XXIII and XXIV.

The data shown in Figs. 2 and 3 are for a single electron energy of 4.5 keV. We have also done a systematic study of thermal plasmas using a Maxwell-Boltzmann electron distribution. This is done by sweeping the electron beam energy much faster than the recombination time. This allows simulation of conditions similar to many astrophysical phenomena. Our studies to date have centered on equilibrium ionization in thermal plasmas. However, in the near future we will study non-equilibrium conditions in thermal plasmas as well. The EBIT I/II facility at LLNL has the ability to inject Fe gas as well as Fe ions from the MEVVA. This allows a very fast injection cycle (<100 ms total) so that we can concentrate on only the non-equilibrium plasma conditions, substantially improving the efficiency. Simultaneous observations using the XRS and high-resolution crystal spectrometers allow us to combine the broadband capabilities of the XRS with the high resolution (< 1 eV FWHM) of the crystal spectrometers over the crucial Fe L shell emission band.

The XRS has been operational at the EBIT I/II facility periodically since July 2000. It will remain at LLNL performing systematic studies of astrophysical plasmas until a permanent fully automatic microcalorimeter instrument is deployed in 2003. We will continue to upgrade the existing instrument with advances in microcalorimeter technology from our laboratory including improved bandpass, energy resolution, and collecting area.

REFERENCES

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